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# Hadronic and rare B decays with the BaBar and Belle experiments\*

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We review recent experimental results on  $B_d$  and  $B_s$  mesons decays by the BaBar and Belle experiments. These include measurements of the color-suppressed decays  $\bar{B}^0 \rightarrow D^{(*)0}h^0, h^0 = \pi^0, \eta, \eta', \omega$ , observation of the baryonic decay  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda} K^-$ , measurements of the charmless decays  $B \rightarrow \eta h, h = \pi, K, B \rightarrow K\pi$ , and observation of CP eigenstates in the  $B_s$  decays:  $B_s^0 \rightarrow J/\psi f_0(980)$ ,  $B_s^0 \rightarrow J/\psi f_0(1370)$  and  $B_s^0 \rightarrow J/\psi \eta$ . The theoretical implications of these results will be considered.

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## 1. Introduction

Given the large mass of the top quark,  $B$  mesons are the only weakly decaying mesons containing quarks of the third generation. Their decays are thus a unique window on the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, describing the couplings of the third generation of quarks to the lighter quarks. Hadronic  $B$  mesons decays occur primarily through the Cabibbo favored  $b \rightarrow c$  transition. In the Standard Model these decays can also occur through Cabibbo suppressed  $b \rightarrow u$  transitions or through one loop diagrams, such as penguin diagrams, which involve a virtual  $W^\pm$  boson and a heavy quark. This proceeding reviews recent results [1][2][3][4][5][6] from the BaBar [7] and Belle [8] experiments which took data during the past decade at the high luminosity  $B$ -factories PEP-II [9] and KEKB [10].

## 2. Color-suppressed decays $\bar{B}^0 \rightarrow D^{(*)0}h^0, h^0 = \pi^0, \eta, \eta', \omega$

In such decays, the effect of color suppression is obscured by the exchange of soft gluons (final state interactions), which enhance  $W^\pm$  exchange diagrams. Previous measurements of the branching fractions of the color-suppressed decays  $\bar{B}^0 \rightarrow D^{(*)0}h^0$  invalidated the factorization

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model [11][12][13]. However more precise measurements are needed to confirm that result and to constrain the different QCD models: SCET (Soft Collinear Effective Theory) and pQCD (perturbative QCD). BaBar measured the branching fractions from exclusive reconstruction using a data sample of  $454 \times 10^6 B\bar{B}$  pairs [1], the measured values can be found in the Table 1 compared to theoretical predictions. The values measured are higher by a factor of about three to five than the values predicted by factorization. The pQCD predictions are closer to experimental values but are globally higher, except for the  $D^{(*)0}\pi^0$  modes. SCET [14][15][16] does not give prediction on the branching fractions themselves, but predicts that the ratios  $BF(\bar{B}^0 \rightarrow D^{*0}h^0)/BF(\bar{B}^0 \rightarrow D^0h^0)$  are about equal to one for  $h^0 = \pi^0, \eta, \eta'$ . The ratios of branching fractions are given in Table 2 and are compatible with one. This SCET prediction holds only for the longitudinal component  $\bar{B}^0 \rightarrow D^{(*)0}h^0$ , in the case of  $h^0 = \omega$  nontrivial long-distance QCD interactions may increase the transverse amplitude. The longitudinal fraction  $f_L$  of  $B$  decays to a pair of vector mesons is predicted to be one in the factorization description. The longitudinal fraction of the decay  $\bar{B}^0 \rightarrow D^{(*)0}\omega$  was measured for the first time in the same data sample, yielding  $f_L = (66.5 \pm 4.7(\text{stat.}) \pm 1.5(\text{syst.}))\%$  [1], deviating thus significantly from the factorization's prediction. This reinforces the conclusion drawn from the branching fraction measurements on the validity of factorization in color-suppressed decays and supports expectations from SCET.

Table 1. Comparison of the measured branching fractions  $BF$ , with the predictions by factorization [17, 18, 19, 20] and pQCD [21, 22]. The first quoted uncertainty is statistical and the second is systematic.

$BF (\times 10^{-4})$	This measurement	Factorization	pQCD
$B^0 \rightarrow D^0\pi^0$	$2.69 \pm 0.09 \pm 0.13$	0.58 [17]; 0.70 [18]	2.3-2.6
$\bar{B}^0 \rightarrow D^{*0}\pi^0$	$3.05 \pm 0.14 \pm 0.28$	0.65 [17]; 1.00 [18]	2.7-2.9
$\bar{B}^0 \rightarrow D^0\eta$	$2.53 \pm 0.09 \pm 0.11$	0.34 [17]; 0.50 [18]	2.4-3.2
$\bar{B}^0 \rightarrow D^{*0}\eta$	$2.69 \pm 0.14 \pm 0.23$	0.60 [18]	2.8-3.8
$\bar{B}^0 \rightarrow D^0\omega$	$2.57 \pm 0.11 \pm 0.14$	0.66 [17]; 0.70 [18]	5.0-5.6
$\bar{B}^0 \rightarrow D^{*0}\omega$	$4.55 \pm 0.24 \pm 0.39$	1.70 [18]	4.9-5.8
$\bar{B}^0 \rightarrow D^0\eta'$	$1.48 \pm 0.13 \pm 0.07$	0.30-0.32 [20]; 1.70-3.30 [19]	1.7-2.6
$\bar{B}^0 \rightarrow D^{*0}\eta'$	$1.48 \pm 0.22 \pm 0.13$	0.41-0.47 [19]	2.0-3.2

Table 2. Ratios of branching fractions  $BF(\bar{B}^0 \rightarrow D^{*0}h^0)/BF(\bar{B}^0 \rightarrow D^0h^0)$ . The first uncertainty is statistical, the second is systematic.

$BF$ ratio	This measurement
$D^{*0}\pi^0/D^0\pi^0$	$1.14 \pm 0.07 \pm 0.08$
$D^{*0}\eta(\gamma\gamma)/D^0\eta(\gamma\gamma)$	$1.09 \pm 0.09 \pm 0.08$
$D^{*0}\eta(\pi\pi\pi^0)/D^0\eta(\pi\pi\pi^0)$	$0.87 \pm 0.12 \pm 0.05$
$D^{*0}\eta/D^0\eta$ (Combined)	$1.03 \pm 0.07 \pm 0.07$
$D^{*0}\omega/D^0\omega$	$1.80 \pm 0.13 \pm 0.13$
$D^{*0}\eta'(\pi\pi\eta)/D^0\eta'(\pi\pi\eta)$	$1.03 \pm 0.22 \pm 0.07$
$D^{*0}\eta'(\rho^0\gamma)/D^0\eta'(\rho^0\gamma)$	$1.06 \pm 0.38 \pm 0.09$
$D^{*0}\eta'/D^0\eta'$ (Combined)	$1.04 \pm 0.19 \pm 0.07$

### 3. Baryonic decay $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda} K^-$

Baryonic decays account for  $(6.8 \pm 0.6)\%$  [23] of all  $B$  mesons decays, however little is known about these processes. The reconstruction of exclusive final states allow to compare decay rates, and hence to increase our understanding of the fragmentation of  $B$  mesons into hadrons. The first measurement of the decay channel  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda} K^-$  is reported here [2], using the full BaBar  $\Upsilon(4S)$  sample, thus  $471 \times 10^6 B\bar{B}$  pairs. The background-subtracted distributions of the invariant masses  $m(\Lambda_c K)$ ,  $m(\Lambda_c \Lambda)$  and  $m(\Lambda_c \bar{K})$  are given in the Fig. 1. A resonant structure is observed above  $3.5 \text{ GeV}/c^2$  in  $m(\Lambda_c K)$ , while no threshold enhancement is observed in  $m(\Lambda_c \Lambda)$ , in contrary to other three-body baryonic  $B$  decays [24]. The branching fraction is measured after rescaling the simulated efficiency to the data distribution, yielding:  $BF(\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda} K^-) = (3.8 \pm 0.8(\text{stat.}) \pm 0.2(\text{syst.}) \pm 1.0(\Lambda_c^+)) \times 10^{-5}$  [2], where the third uncertainty arises from uncertainty on the branching fraction of  $\Lambda_c^+ \rightarrow pK^-\pi^+$ . This is the first measurement of this channel, with a significance above seven standard deviations.

### 4. Charmless decays $B \rightarrow \eta h$ ( $h = \pi, K$ )

Charmless decays are sensitive probes for the measurement of the CP violation. In the Standard Model, the decays  $B \rightarrow \eta K$  proceed through  $b \rightarrow s$  penguin and  $b \rightarrow u$  tree transitions. The interference of these transitions can result in a large direct CP asymmetry  $A_{CP}$  [25], defined as:

$$A_{CP} = \frac{\Gamma(\bar{B} \rightarrow \eta h) - \Gamma(B \rightarrow \eta \bar{h})}{\Gamma(\bar{B} \rightarrow \eta h) + \Gamma(B \rightarrow \eta \bar{h})}, \quad (1)$$

where  $\Gamma(B \rightarrow \eta h)$  is the partial width obtained for the  $B \rightarrow \eta h$  decay. Similar non-zero direct CP violation could be observed for  $B^+ \rightarrow \eta \pi^+$ , given to the interference between  $b \rightarrow d$  penguin and  $b \rightarrow u$  tree diagrams. Previous measurements by Belle [26] and BaBar [27] pointed to large negative  $A_{CP}$ , but preciser measurements are necessary to exclude the non-zero  $A_{CP}$  in  $B^+ \rightarrow \eta \pi^+$ . The branching fractions and  $A_{CP}$  (for the charged modes) has been measured in the final Belle data sample [3], thus  $772 \times 10^6 B\bar{B}$ , and are given in the Table 3. The first observation of  $B^0 \rightarrow \eta K^0$  is also reported, with a significance of  $5.4\sigma$  [3].

Table 3. Measured branching fractions  $BF$  and direct CP asymmetry  $A_{CP}$  of  $B \rightarrow \eta h$ ,  $h = K, \pi$ . The first uncertainty is statistical, the second is systematic.

Observables	Measured values
$BF(B^0 \rightarrow \eta K^0)$	$(1.27^{+0.33}_{-0.29} \pm 0.08) \times 10^{-6}$
$BF(B^+ \rightarrow \eta K^+)$	$(2.12 \pm 0.23 \pm 0.11) \times 10^{-6}$
$BF(B^+ \rightarrow \eta \pi^+)$	$(4.07 \pm 0.26 \pm 0.21) \times 10^{-6}$
$A_{CP}(B^+ \rightarrow \eta K^+)$	$-0.38 \pm 0.11 \pm 0.01$
$A_{CP}(B^+ \rightarrow \eta \pi^+)$	$-0.19 \pm 0.06 \pm 0.01$

## 5. Charmless decays $B \rightarrow K\pi$

In a similar way as for the  $B \rightarrow \eta h$  decays (see Section 4), the  $B \rightarrow K\pi$  channels proceed through two diagrams:  $b \rightarrow u$  tree and  $b \rightarrow s$  penguins ones, both color-allowed or color-suppressed [28], whose interference are predicted to lead to a non-null direct CP asymmetry  $A_{CP}(K^\pm \pi^\mp)$ :

$$A_{CP}(K^\pm \pi^\mp) = \frac{\Gamma(\bar{B}^0 \rightarrow K^- \pi^+) - \Gamma(B^0 \rightarrow K^+ \pi^-)}{\Gamma(\bar{B}^0 \rightarrow K^- \pi^+) + \Gamma(B^0 \rightarrow K^+ \pi^-)}. \quad (2)$$

Previous measurements of the direct CP asymmetry in  $B \rightarrow K\pi$  decays by Belle [28] pointed a significant and unexplained difference between  $A_{CP}(K^\pm \pi^\mp)$  and  $A_{CP}(K^\pm \pi^0)$ . Using the final sample, thus  $772 \times 10^6 B\bar{B}$  pairs plus an improved tracking, Belle measured the branching fractions and the direct asymmetries of  $B \rightarrow K\pi$  modes [4] (see Table 4). These values are compatible with the previous measurements by BaBar [29], CDF [30] and LHCb [31]. The possible isospin violating in  $B \rightarrow K\pi$  decays can be investigated comparing the  $BF$  ratios between the different modes with the SM prediction from the  $SU(3)$  symmetry. The results, given in the Table 5 are consistent with the different theoretical approaches [4].

Table 4. Measured branching fractions  $BF$  and direct CP asymmetry  $A_{CP}$  of  $B \rightarrow K\pi$ . The first uncertainty is statistical, the second is systematic.

Channel	$BF$	$A_{CP}$
$B^\pm \rightarrow K^\pm \pi^0$	$(12.62 \pm 0.31 \pm 0.56) \times 10^{-6}$	$0.043 \pm 0.024 \pm 0.002$
$B^0 \rightarrow K^\pm \pi^\mp$	$(20.00 \pm 0.34 \pm 0.63) \times 10^{-6}$	$-0.069 \pm 0.014 \pm 0.007$
$B^\pm \rightarrow K^0 \pi^\pm$	$(23.97^{+0.53}_{-0.52} \pm 0.69) \times 10^{-6}$	$-0.014 \pm 0.021 \pm 0.006$
$B^0 \rightarrow K^0 \pi^0$	$(9.66 \pm 0.46 \pm 0.49) \times 10^{-6}$	—

Table 5. Widths  $\Gamma$  ratios derived from the measured branching fractions (see Table 4), compared to the SM prediction from the  $SU(3)$  symmetry. The first uncertainty is statistical, the second is systematic.

Ratio	This measurement	$SM$
$2\Gamma(K^+\pi^0)/\Gamma(K^0\pi^+)$	$1.05 \pm 0.03 \pm 0.05$	$1.15 \pm 0.05$
$\Gamma(K^+\pi^-)/2\Gamma(K^0\pi^0)$	$1.04 \pm 0.05 \pm 0.06$	$1.12 \pm 0.05$

## 6. Observations of $B_s^0 \rightarrow J/\psi f_0$ and $B_s^0 \rightarrow J/\psi \eta$

The  $b \rightarrow c\bar{c}s$  transition, occurring for instance in the decay  $B_s^0 \rightarrow J/\psi \phi$ , benefits from a relatively large branching fraction. It has thus been used to extract the  $B_s^0$  decay width difference  $\Delta\Gamma$  and the CP violating phase  $\beta_s$  [32][33], sensitive to potential New Physics. Such study requires however an angular analysis, owing to the *Scalar* $\rightarrow$ *Vector Vector* nature of the channel. The same  $b \rightarrow c\bar{c}s$  transition can lead to the decay channel  $B_s^0 \rightarrow J/\psi f_0$ , thus *Scalar* $\rightarrow$ *Vector Scalar*, for which no angular analysis is so needed; furthermore leading order QCD, together with measurements of  $D_s$  decays to  $\phi$  and  $f_0$  mesons, predicts its branching fraction to be  $(3.1 \pm 2.4) \times 10^{-4}$  [5]. Using its final data sample at  $\Upsilon(5S)$ , thus  $121.4/fb$  or  $(1.24 \pm 0.23) \times 10^7$   $B_s^* \bar{B}_s^*$  pairs, Belle measured the  $B_s^0 \rightarrow J/\psi f_0$  branching fraction, yielding together with LHCb [34] its first observation [5]. The distributions of the invariant mass of the di-pion system from  $f_0 \rightarrow \pi^+\pi^-$  are given in the Figure 2, where the  $f_0(980)$  resonance can be seen, close to another scalar resonance, whose fitted parameters are:  $m_0 = (1.405 \pm 0.015(\text{stat.})^{+0.001}_{-0.007}(\text{syst.}))$  GeV/ $c^2$  and  $\Gamma_0 = (0.054 \pm 0.033(\text{stat.})^{+0.014}_{-0.003}(\text{syst.}))$  GeV, which are consistent with the  $f_0(1370)$  parameters [23]. The measured branching fractions, signal yields and significances are given in the Table 6.

Belle also observed for the first time the decay  $B_s^0 \rightarrow J/\psi \eta$  using its full  $\Upsilon(5S)$  dataset [6]. The distributions in data of the beam-constrained mass

Table 6. Branching fractions, fitted signal yields and significance  $S$  of the measurements performed in data on the  $B_s^0 \rightarrow J/\psi f_0(X)$  channels. The quoted uncertainties account for respectively the statistics, systematics and the number of  $B_s^{(*)} \bar{B}_s^{(*)}$  in the data sample.

Mode	Yield	$S$	$BF \times 10^{-4}$
$B_s^0 \rightarrow J/\psi f_0(980)$	$63_{-10}^{+16}$	$8.4\sigma$	$1.16_{-0.19-0.17-0.18}^{+0.31+0.15+0.26}$
$B_s^0 \rightarrow J/\psi f_0(1370)$	$19_{-8}^{+6}$	$4.2\sigma$	$0.34_{-0.14-0.02-0.05}^{+0.11+0.03+0.08}$

$M_{bc}$  and of the energy difference  $\Delta E$  [5] for the sub-channel  $B_s^0 \rightarrow J/\psi \eta$  with  $\eta \rightarrow \pi^+ \pi^- \pi^0$  are given in the Figure 3 where the  $B$  signal can clearly be seen at  $M_{bc} \simeq 5.42 \text{ GeV}/c^2$  and  $\Delta E \simeq 0 \text{ GeV}$ . The measured branching fraction yields:

$$BF(B_s^0 \rightarrow J/\psi \eta) = (5.11 \pm 0.50(\text{stat.}) \pm 0.35(\text{syst.}) \pm 0.68(f_s) \times 10^{-4}), \quad (3)$$

where the last uncertainty accounts for the  $B_s^{(*)} \bar{B}_s^{(*)}$  production fraction at the  $\Upsilon(5S)$ .

The observation of these channels offers new CP channels for the study of the  $B_s$  mixing property, paving the way for LHC experiments.

## REFERENCES

- [1] BaBar Collaboration. *Phys. Rev. D*, 84:112007, 2011.
- [2] BaBar Collaboration. *Phys. Rev. D*, 84:071102, 2011.
- [3] C.-T. Hoi and P. Chang for the Belle Collaboration. In *Belle Preprint 2011-14 arXiv:1110.2000v1 [hep-ex]*, 2011.
- [4] Paoti Chang for the Belle Collaboration. In *Proceedings for EPS-HEP Grenoble*, 2011.
- [5] Belle Collaboration. *Phys. Rev. Lett.*, 106:121802, 2011.
- [6] Belle Collaboration. In [http://belle.kek.jp/results/summer11/Bs\\_JpsiEta/](http://belle.kek.jp/results/summer11/Bs_JpsiEta/), 2011.
- [7] BaBar Collaboration. *Nucl. Instrum. Methods A*, 479:1, 2002.
- [8] A. Abashian et al. *Nucl. Instrum. Methods, A* 479:117, 2002.
- [9] PEP-II. In *Conceptual Design Report, SLAC-0418*, 1993.
- [10] S. Kurokawa and E. Kikutani. *Nucl. Instrum. Methods A*, 499:1, 2003.
- [11] BaBar Collaboration. *Phys. Rev. D*, 69:032004, 2004.
- [12] Belle Collaboration. *Phys. Rev. D*, 72:011103, 2005.

- [13] Belle Collaboration. *Phys. Rev. D*, 74:092002, 2006.
- [14] C.W. Bauer, D. Pirjol, and I.W. Stewart. *Phys. Rev. D*, 65:054022, 2002.
- [15] A.E. Blechman, S. Mantry, , and I.W. Stewart. *Phys. Lett. B*, 608:77, 2005.
- [16] S. Mantry, D. Pirjol, , and I.W. Stewart. *Phys. Rev. D*, 68:114009, 2003.
- [17] C.K. Chua, W.S. Hou, and K.C. Yang. *Phys. Rev. D*, 65:096007, 2002.
- [18] M. Neubert and B. Stech. In *Heavy Flavours II*, eds. A.J. Buras and M. Lindner (World Scientific, Singapore, 1998), p. 294., 1998.
- [19] A. Deandrea and A.D. Polosa. *Eur. Phys. J.*, 677:22, 2002.
- [20] J.O. Eeg, A. Hiorth, and A.D. Polosa. *Phys. Rev. D*, 65:054030, 2002.
- [21] Y.Y. Keum, T. Kurimoto, H. Li, C.D. Lü, and A.I. Sanda. *Phys. Rev. D*, 69:094018, 2004.
- [22] C.D. Lü. *Phys. Rev. D*, 68:097502, 2003.
- [23] K. Nakamura et al. (Particle Data Group). *J. Phys. G*, 37:075021, 2010.
- [24] Xavier Prudent for the BaBar Collaboration. In *Proceedings for ICHEP2008*, *arXiv:0809.2929v2 [hep-ex]*, 2008.
- [25] H. J. Lipkin. *Phys. Lett. B*, 254:247, 1991.
- [26] Belle Collaboration. *Phys. Rev. D*, 75:071104, 2007.
- [27] BaBar Collaboration. *Phys. Rev. D*, 80:112002, 2009.
- [28] Belle Collaboration. *Nature*, 452:332, 2008.
- [29] BaBar Collaboration. In *Proceedings for ICHEP2008*, *arXiv:0807.4226 [hep-ex]*, 2008.
- [30] CDF Collaboration. *Phys. Rev. Lett.*, 106:181802, 2011.
- [31] LHCb Collaboration. In *arXiv:1106.1197 [hep-ex]*, 2011.
- [32] CDF Collaboration. *Phys. Rev. Lett.*, 100:161802, 2008.
- [33] D0 Collaboration. *Phys. Rev. Lett.*, 101:241801, 2008.
- [34] LHCb Collaboration. *Phys. Rev. Lett. B*, 698:115–122, 2011.



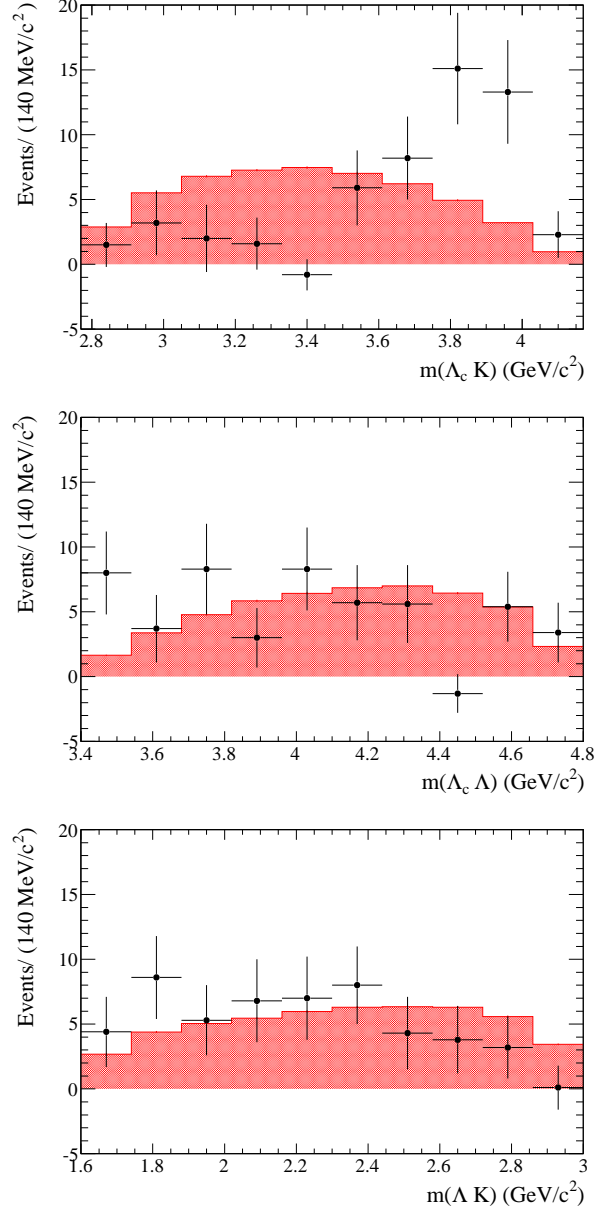


Fig.1. Background-subtracted distributions of the invariant masses  $m(\Lambda_c K)$ ,  $m(\Lambda_c \Lambda)$  and  $m(\Lambda K)$  in data (points) and simulated Monte Carlo non-resonant signal sample (full histogram)

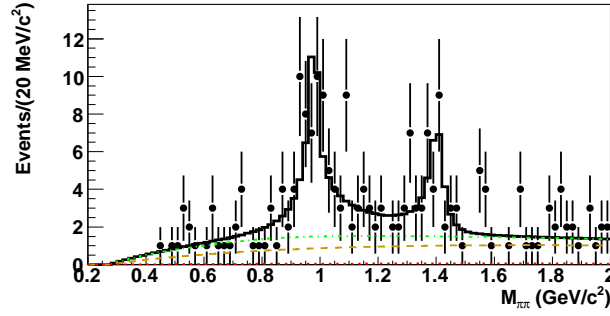


Fig. 2. Invariant mass of the di-pion system in data (points). The total fitted distribution is given by the solid line, the dash-dotted curve give the total background, the dashed curves other  $J/\psi$  background, and the dotted curves show the non-resonant component.

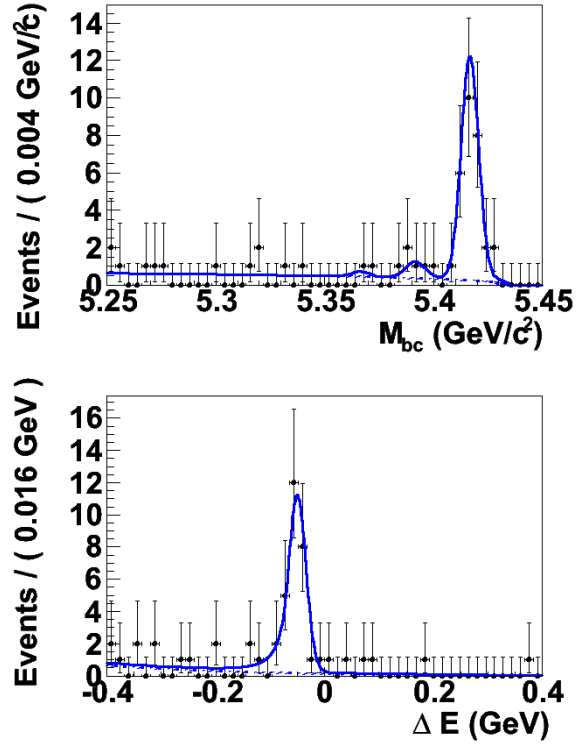


Fig. 3. The distributions in data (points) of the beam-constrained mass  $M_{bc}$  and of the energy difference  $\Delta E$  for the sub-channel  $B_s^0 \rightarrow J/\psi \eta$  with  $\eta \rightarrow \pi^+ \pi^- \pi^0$ . The total fit function is given by the solid line, the total background contribution by the dotted line, and the continuum background is represented by the dashed line.